

Dissolved organic matter and its role in the soil solution chemistry in relation to organic matter accumulation on the forest floor

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The aim of this study was to determine how accumulation of organic matter on the forest floor (logging residue piles) is reflected in the soil solution concentrations of dissolved organic C and N and other nutrients. The data were collected from a logging residue experiment 7 years after a clear-cut harvest of a Norway spruce stand growing on sandy soil. The solution retained in the soil matrix was extracted from soil samples by the centrifugation method. The study site was located in Paltamo, Finland. The logging residue levels were: (1) 40 kg m⁻², (2) 10 kg m⁻², and (3) 0 kg m⁻² of fresh spruce branches. The DOC and DON concentrations were higher in the organic layer in the centrifuged soil solution due to organic matter accumulation on the forest floor as compared to the treatment where no accumulation had occurred, and these higher levels were persisting still seven years after the logging residues had been piled on the site. The NO₃-N and NH₄-N concentrations were generally very low. It was possible to accurately estimate the anion deficit based on the DOC concentration in the soil solution, and the increased concentration of DOC and organic anions strongly influenced the ionic balance of the centrifuged soil solution.

Introduction

In the forest ecosystems the amount of dissolved organic carbon (DOC) and nitrogen (DON) are relatively small in the deposition, stand through-fall and percolation water as compared to the C and N stocks in its other components, e.g. trees, ground vegetation and soil (e.g. Piirainen 2002, Piirainen *et al.* 2002, Lindroos *et al.* 2008, Mustajärvi *et al.* 2008, Merilä *et al.* 2014). However, the DOC and DON concentrations and fluxes play important roles in many processes affecting

the nutrient cycling in forest ecosystems. Dissolved organic matter (DOM) acts as an organic anion affecting the ionic balance of the soil water (Lundström 1993, Lindroos *et al.* 1995), and strongly influences the presence of other soil water ions. The DOM forms complexes with Fe and Al, and plays a central role in the weathering and podzolisation processes in the forest soil (e.g. Berggren 1992, Raulund-Rasmussen *et al.* 1998, Lundström *et al.* 2000a, 2000b, Lindroos *et al.* 2011). In undisturbed forest ecosystems nitrogen leaching mainly occurs through the leaching of

DON, because leaching of inorganic forms of N is often negligible (Mustajärvi *et al.* 2008). Despite DON leaching, the total N leaching in undisturbed and managed boreal forests in Finland have been reported to be relatively low (Mustajärvi *et al.* 2008).

Following clear-cutting, there is an immediately increased input of organic matter into the forest soil due to the logging residues (Rosén and Lundmark-Thelin 1987, Piirainen 2002), and increased mineralization of organic matter has widely been reported after clear-cut harvesting (e.g. Smolander *et al.* 1998). It has been reported that leaching of DOC and DON from the organic layers has increased due to clear cutting and logging residues (Piirainen *et al.* 2002), but leaching below the B horizon of podzolic soils has been relatively low due to the retention of DOM related to the podzolisation processes (Piirainen *et al.* 2002, Lindroos *et al.* 2016).

The role of logging residues and clear-cutting on the percolation water quality has been studied largely (e.g. Rosén and Lundmark-Thelin 1987, Mann *et al.* 1988, Kubin 1998, Piirainen *et al.* 2002, Wall 2008, Morris 2009, Lindroos *et al.* 2016). The amount and distribution of logging residues on a clear-cut area may have a strong impact on the soil water quality (Rosén and Lundmark-Thelin 1987, Morris 2009, Lindroos *et al.* 2016). Therefore, controlled logging residue experiments may provide a valuable tool to study how the soil water quality is affected by organic matter accumulation on the forest floor.

The typical amount of logging residue left on the site is 3–7 kg m⁻² (d.w.) for Norway spruce stands in clear-cutting and stem-only harvesting in Finland (Piirainen 2002, Saksa *et al.* 2002, Ukonmaanaho *et al.* 2008, Peltola *et al.* 2011). However, this logging residue amount is not normally evenly distributed, and the sizes of the logging residue piles may vary considerably on clear-cut areas, 0–36.5 kg m⁻², which means that there may be large accumulations on restricted parts of the site as well as large areas without piles although some logging residue may occur (Rosén and Lundmark-Thelin 1987).

Soil solution chemistry has been largely studied based on the collection of percolation water by zero-tension lysimeters (Rosén and Lundmark-Thelin 1987, Piirainen *et al.* 2002, Wall 2008,

Lindroos *et al.* 2016). Techniques based on zero-tension are useful in leaching studies, but they do not collect the water retained in the soil matrix, which is an important consideration when studying soil processes such as weathering of minerals, equilibria between soil and water and possibly also the nutrient supply to plant roots particularly during dry periods, since the roots are able to utilize tightly bound water. It has also been reported that the chemical composition of the water may vary in the different fractions of the soil water, e.g. between the water collected by zero-tension and suction-cup lysimeters (Derome *et al.* 2001) and between the water collected by zero-tension lysimeters and soil solution extracted from the soil samples by the centrifugation method (Giesler *et al.* 1996). There are also only a few studies conducted in the boreal forests of the Nordic countries related to the soil solution composition based on the centrifugation method (e.g. Giesler *et al.* 1996, Gustafsson *et al.* 2000, Tanskanen *et al.* 2004). Centrifugation extracts capillary retained and partly absorbed hygroscopic water from the soil matrix (Derome *et al.* 2001); these water fractions are important in equilibria processes between soil particles and water hold in the soil matrix (Nissinen *et al.* 1998, Nissinen *et al.* 1999), but not so much information is available on the importance of the chemical composition of centrifuged soil solution in the bioavailability of nutrients for plants and microbes.

The aim of this study was to determine how logging residues that have been deposited on the forest floor are reflected in the soil solution concentrations of dissolved organic C and N and mineral nutrients. We used a logging residue experiment established in 2007, and collected data from the experiment 7 years after clear-cut. The solution retained in the soil matrix was extracted from the soil samples by the centrifugation method. We hypothesized that large organic matter accumulations in logging residue piles would result in high concentrations of DOC, DON and nutrients in soil solution and this would affect soil solution chemical equilibria.

Material and methods

The study site was located in Paltamo, Fin-

land (64°27'N, 27°33'E, 206–214 m a.s.l.) in a Norway spruce stand with an average age of 156 years at the time of harvest (completed in 2007). The mean annual temperature in the area is 2.5 °C, and average precipitation 690 mm. The forest site type, according to Finnish classification (Cajander 1949), was of the *Myrtillus* site type (mesic heath forest site type) which means that *Vaccinium myrtillus* was dominant in the ground vegetation. The soil was composed of poorly sorted fine sand and contained only a small proportion of stones (estimated stoniness < 10%), and was classified as a podzol (IUSS Working Group WRB 2006). The soil horizons were clearly identifiable and were as follows: organic layer (Ofh, mor, thickness 7 cm), eluvial horizon (E, 15 cm), illuvial horizon (B, 15 cm), transitional horizon between the B and C (BC, 10 cm), and parent material (C). The organic matter concentrations (LOI, %) by soil horizons were as follows: 86 (O), 0.6 (E), 4.1 (B), 1.3 (BC) and 0.7 (C). Specific soil and stand structure data of the study area are described by Kubin *et al.* (2013) and Tarvainen *et al.* (2015).

Immediately after clear-cutting, the experimental setup was laid out. An experimental area, 30 m × 30 m in size, was restricted from a clear-cut area of several hectares, and 10 small sample plots (1 m × 1 m) were established on the experimental area. In order to minimize natural variation we attempted to select as homogenous areas as possible for the experiment among the sample plots and subsequently to be able to clarify and separate the processes related to logging residue piles from other natural processes. The soil surface of the sample plots was flat and the area as a whole formed a homogenous area in terms of soil texture, and only vertical water flow could be assumed. Using the logging residues generated in clear cutting, three different treatments were established: (1) 40 kg m⁻², (2) 10 kg m⁻², and (3) 0 kg m⁻² of fresh spruce branches. The treatments 1 and 2 consisted of three and treatment 3 of four replicates, one m² each (i.e. 10 plots in total). These sample plots were randomly located on the experimental area, and the location of each treatment plot was randomly chosen among the 10 plots. In order to avoid “edge” effect among the sample plots, they were located at a distance of at least 2 m from each other. One

extra plot was established for the treatment 3) (0 kg logging residues per m²) in order to ensure the baseline value. One replication (one sample plot) of the treatment 10 kg fresh spruce branches per m² was destroyed during the 7-year period after clear-cut probably by animals, and was not sampled.

The soil solution was extracted from soil samples of the O, E, B, BC and C horizons of the podzolic soil below the logging residue at the small sample plots. Four sub-samples were taken from each soil horizon of each sample plot by sampling tubes (length 46 mm, diameter 50 mm). The samples were taken from a soil profile that was dug at one side of each of the sample plots. The sampling tubes were inserted into the soil horizons, removed from the soil profile and sealed with plastic cover in order to keep the soil samples inside the tubes fresh and prevent moisture from evaporating. The samples were collected in September 2014. After sampling, the tubes were immediately transported to the laboratory, and kept cold throughout the sampling, transportation and handling in the laboratory.

In the laboratory, the soil samples were removed from the plastic tubes and placed in centrifuge tubes with porous bottoms and a separate lower cup used to collect the soil solution samples. With a Thermo Scientific Fiberlite F-14-6x250y rotor by Sorvall RC5C centrifuge, the samples were centrifuged for 45 minutes at a speed of 11000 rpm., responding about 19000 × g. The centrifugation temperature was +4 °C. The soil solutions extracted from the four sub-samples of each horizon per sample plot were filtered through a 0.45 μm membrane filter and combined to give one composite sample per horizon.

The concentrations of dissolved organic carbon (DOC) and total nitrogen of each composite soil solution sample were determined by a TOC/TN analyzer (Shimadzu TOC-L_{CSH/CSN}). The NO₃-N and NH₄-N concentrations were determined by spectrophotometric methods (applications of standard methods SFS 3029 and ISO 7150/1, respectively). The concentration of dissolved organic nitrogen (DON) was calculated by subtracting the NO₃-N and NH₄-N from the total N.

For two sample plots of each treatment, the concentrations of Ca, Mg, K, Na, Al, Fe and

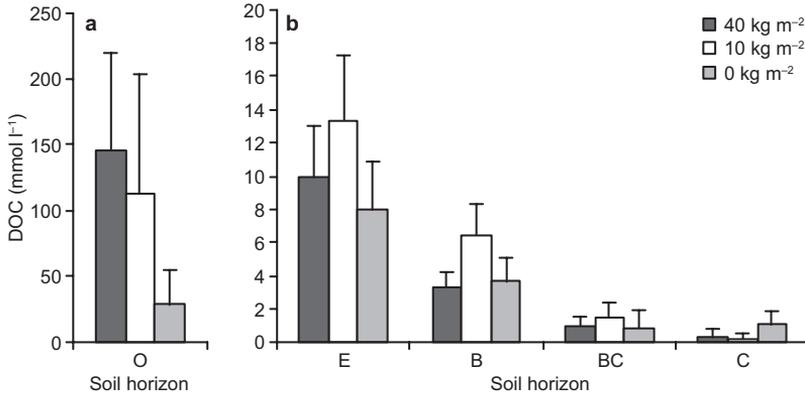


Fig. 1. DOC concentration (+ SD) in soil solution extracted by centrifugation from the treatments: 40 kg logging residues per m² (number of sample plots, $n = 3$), 10 kg m⁻² ($n = 2$) and 0 kg m⁻² ($n = 4$). Soil solution was collected from the (a) O, and (b) E, B, BC and C horizons.

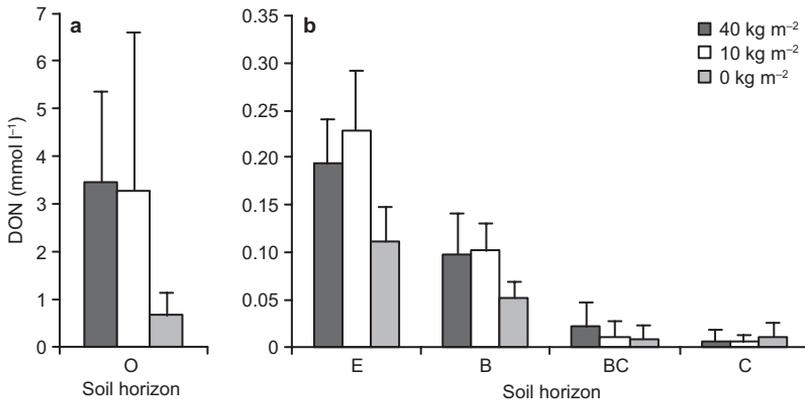


Fig. 2. DON concentration (+ SD) in soil solution extracted by centrifugation from the treatments: 40 kg logging residues per m² (number of sample plots, $n = 3$), 10 kg m⁻² ($n = 2$) and 0 kg m⁻² ($n = 4$). Soil solution was collected from the (a) O, and (b) E, B, BC and C horizons.

Mn were also determined by inductively coupled plasma atomic emission spectrophotometer (ICP-AES, iCAP 6500 Duo analyzer). The concentrations of Cl, SO₄-S and PO₄-P were determined for these samples by ion chromatograph (IC, Dionex ICS-1000). The pH of the samples was also determined. The concentration of organic anions (A⁻) was calculated using Oliver's equation (Oliver *et al.* 1983). We used 6 µeq(mgC)⁻¹ for the m value in Oliver's equation, i.e. the concentration of acidic functional groups per mg DOC. The anion deficit was calculated by subtracting the sum of inorganic anions (meq l⁻¹) from the sum of inorganic cations (meq l⁻¹), i.e. (H⁺ + Ca²⁺ + Mg²⁺ + K⁺ + Na⁺ + Al³⁺ + Fe³⁺ + Mn²⁺ + NH₄⁺) - (Cl⁻ + SO₄²⁻ + NO₃⁻ + PO₄³⁻).

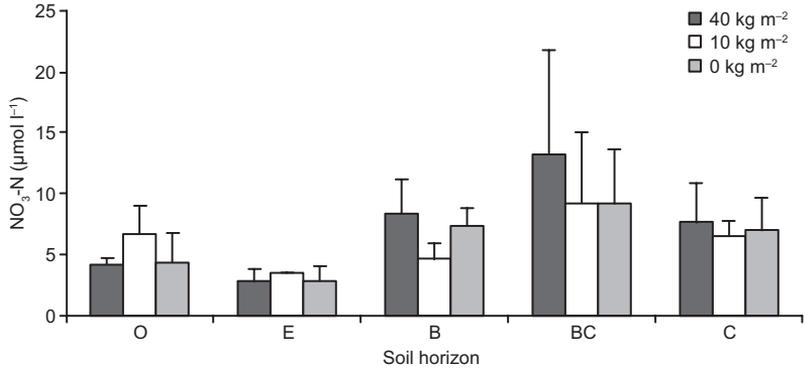
The respective means and standard deviations (SD) were calculated from the replications (replicative sample plots) for each layer in each treatment. The significance of the differences in the values between the no logging-residue treatment and treatments containing logging residues was determined using a non-parametric Mann-

Whitney *U*-test. The differences between the values were regarded as statistically significant at $p < 0.05$. The alternative hypothesis (H_1) was: there are lower values in the no logging-residue treatment than in the treatments containing logging residues. Regression analysis was used to study the relationship between the parameters, and the statistical significance of the coefficient (b) in the regression equation was tested using the *F*-test.

Results

The DOC and DON concentrations in the centrifuged soil solution were higher in the O horizons of the experimental sample plots that contained logging residues (40 kg or 10 kg logging residues per m²) compared to the sampling plots with no logging residues (Figs. 1 and 2). The differences between the combined data from the treatments 40/10 kg m⁻² ($n = 5$) and 0 kg m⁻² ($n = 4$) logging residues were statistically significant

Fig. 3. $\text{NO}_3\text{-N}$ concentration (+ SD) in soil solution extracted by centrifugation from the treatments: 40 kg logging residues per m^2 (number of sample plots, $n = 3$), 10 kg m^{-2} ($n = 2$) and 0 kg m^{-2} ($n = 4$). Soil solution was collected from the O, E, B, BC and C horizons.



for the soil solution of the O horizon (DOC: $U = 2$, $p = 0.032$; DON: $U = 2$, $p = 0.032$) as well as not significant between the mean values of the treatments 40 kg m^{-2} logging residues ($n = 3$) and 0 kg m^{-2} logging residues ($n = 4$) (DOC: $U = 1$, $p = 0.057$; DON: $U = 1$, $p = 0.057$). The treatment 10 kg m^{-2} was not included in the statistical tests as a separate treatment because it contained only two composite samples (replicates) because one of the plots had been destroyed.

The DON concentrations were also higher in the E horizon on the plots with logging residue treatments compared with the no logging residue treatment (40/10 kg m^{-2} vs. 0 kg m^{-2} : $U = 1$, $p = 0.016$; 40 kg m^{-2} vs. 0 kg m^{-2} : $U = 1$, $p = 0.057$) (Fig. 2). The DON concentrations were also significantly higher in the B horizon from the treatments with logging residues compared to the no logging-residue treatment (40/10 kg m^{-2} vs. 0 kg m^{-2} : $U = 0$, $p = 0.008$; 40 kg m^{-2} vs. 0 kg m^{-2} : $U = 0$, $p = 0.028$) (Fig. 2). The DOC and DON concentrations in the BC and C horizons did not differ between the treatments containing logging residues and no logging-residue treatment.

There were no statistically significant differences between the $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations in any soil horizon between the treatments with logging residues and no logging-residue treatment (Fig. 3, $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$ data not shown).

There was a significant positive relationship between the DOC and DON concentrations in the centrifuged soil solution in the O and E horizons in the combined data from all the treatments (Fig. 4).

The ionic balance (meq l^{-1}) in the organic layer between anions (organic anion A^- (esti-

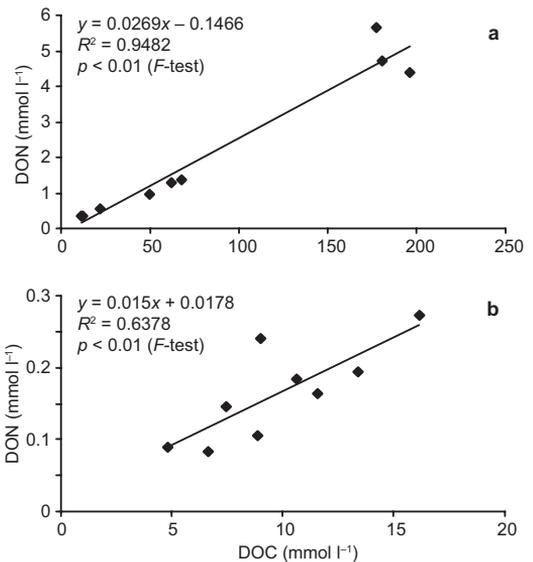


Fig. 4. Relationship between the DOC and DON concentrations in soil solution extracted by centrifugation from the (a) O and (b) E horizons. Data from all the treatments and sample plots ($n = 9$) are combined. Statistical significance of F -test is indicated for the regressions.

mated, Oliver *et al.* 1983), Cl^- , SO_4^{2-} , NO_3^- , PO_4^{3-}) and cations (H^+ , Ca^{2+} , Mg^{2+} , K^+ , Na^+ , Al^{3+} , Fe^{3+} , Mn^{2+} , NH_4^+) was studied for two of the experimental sample plots of each treatment (Fig. 5). The organic anion was the dominant anion in all the treatments (Fig. 5). The concentration of organic anions was higher in the treatments with logging residues as compared to the no logging-residue treatment.

The estimated organic anion concentration (A^- ; Oliver *et al.* 1983) explained the calculated anion deficit (Fig. 6a). In the regression analysis

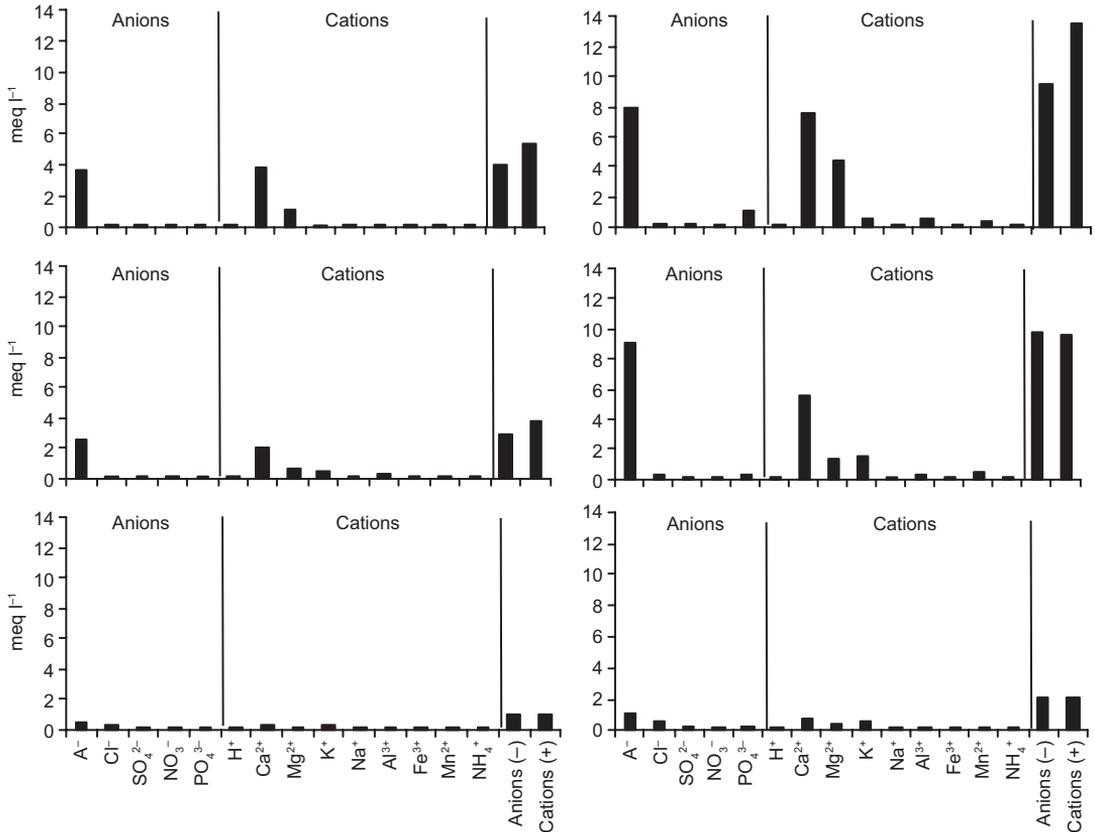


Fig. 5. Concentrations of anions and cations (meq l^{-1}) in soil solution extracted by centrifugation from the organic layer on two plots of the treatments $40 \text{ kg logging residues per m}^2$ (top row), 10 kg m^{-2} (middle row) and 0 kg m^{-2} (bottom row). A⁻ is organic anion calculated with the Oliver's equation (Oliver *et al.* 1983).

the DOC also significantly explained the anion deficit (Fig. 6b).

Discussion

The DOC concentrations in the organic layer were much higher in the centrifuged soil solution extracted from below the organic matter accumulations (logging residue piles) than from the plots without logging residue. The DOC concentrations were much higher in the centrifuged soil solution in the organic layer as compared with the DOC concentrations of freely draining percolation water reported for growing or mature forest stands as well as after clear-cutting (Pirainen *et al.* 2002, Lindroos *et al.* 2008, Lindroos *et al.* 2011). The mean DOC concentration in the organic layer in the treatment 0 kg

logging residues per m^2 was 340 (SD = 319) mg l^{-1} , in centrifuged soil solution in this study which is a high concentration as compared with the mean DOC concentration of ca. 50 mg l^{-1} in the percolation water from the organic layer in 70 year-old spruce, pine and birch stands in northern Finland (Lindroos *et al.* 2011), 60–205 year old pine and spruce stands in different parts of Finland (Level II plots, ICP Forests Programme, Lindroos *et al.* 2008), and after a clear-cut of a spruce dominated mixed stand in eastern Finland (Pirainen *et al.* 2002).

The high concentrations in the centrifuged soil solution demonstrate that the soil solution largely reflects in situ processes in the organic layer and is not directly linked to the concentrations in leaching water from this layer. The DOC concentrations in the centrifuged soil solution in our study agree well with the values reported by

Gustafsson *et al.* (2000) for the podzolic soils in the Nordic countries. Derome *et al.* (2001) and Giesler *et al.* (1996) also reported that the concentrations in a soil solution that is more tightly bound to the soil matrix are different than those in freely draining percolation water, and therefore suggest that a centrifuged soil solution reflects the different fractions of soil water and different processes than percolating water, although the differences in methods themselves also undoubtedly lead to different results. The reason for the high DOC concentrations in centrifuged soil solution in the organic layer is probably related to the close contact of soil solution and microbes responsible for the organic matter degradation leading to high DOC values. The soil solution is at least partly retained as a film or coating on the surfaces of the solid organic material in the O horizon.

In the BC and C horizons the DOC concentrations in the centrifuged soil solution were low. The DOC concentrations in the centrifuged soil solution were relatively similar to those reported for freely draining percolation water below the rooting zone (depth 40 cm) studied in exactly the similar type of logging residue experiment three years after clear cut (Lindroos *et al.* 2016). The mean DOC concentrations in the centrifuged soil solution were 12.1 (SD = 6.2) (treatment 40 kg logging residues per m²), 17.9 (SD = 10.7) (treatment 10 kg m⁻²) and 10.6 (SD = 12.6) mg l⁻¹ (treatment 0 kg m⁻²) in BC horizon, and 3.5 (SD = 6.1), 2.6 (SD = 3.7) and 12.6 (SD = 9.8) mg l⁻¹ in the C horizon, respectively. Correspondingly, the mean DOC concentrations for the two plots in the percolation water at a depth of 40 cm were 7.7 (SD = 1.2) and 6.3 (SD = 0.40) for the treatment 40 kg logging residue per m², 4.4 (SD = 3.7) and 27.3 (SD = 4.10) (treatment 10 kg m⁻²), and 4.3 (SD = 3.5) and 13.8 (SD = 2.90) mg l⁻¹ (treatment 0 kg m⁻²) (Lindroos *et al.* 2016). Comparable and low values in both the water types reflect that the podsolization processes lead to low C concentrations and amounts in the soil as well as low DOC values in the percolation water below the B horizon (Lindroos *et al.* 2016). As part of the podsolization process, the DOC in the percolation water is precipitated out as it passes down through the B horizon.

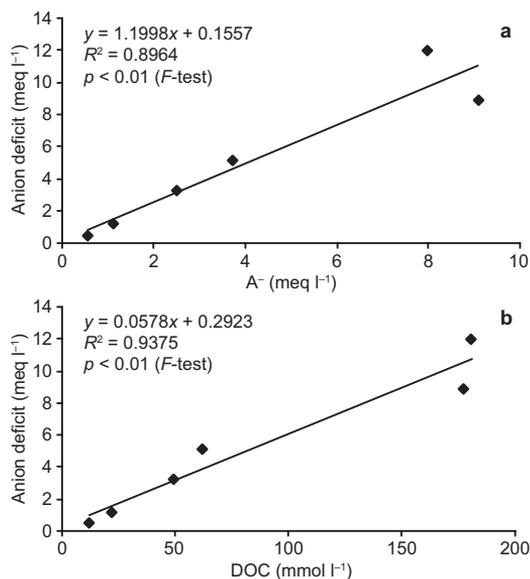


Fig. 6. Relationship between (a) estimated organic anion (A⁻; Oliver *et al.* 1983) and anion deficit (meq l⁻¹), and (b) DOC and anion deficit in soil solution extracted by centrifugation from organic layer. Data from all the treatments and sample plots ($n = 6$) are combined. Statistical significance of *F*-test is indicated for the regressions.

The DOC and DON concentrations in the centrifuged soil solution in the organic layer were higher on the plots with logging residues than on the plots without logging residues. As expected, there was a strong positive relationship between the DOC and DON concentrations in the centrifuged soil solution. The mean DON concentrations in the organic layer in the centrifuged soil solution of 48.6 (SD = 26.5) (treatment 40 kg logging residues per m²), 46.2 (SD = 46.3) (10 kg m⁻²) and 9.1 (SD = 6.7) mg l⁻¹ (0 kg m⁻²) were much higher compared to the respective values in freely draining percolation water from the organic layer generally measured in Finnish forest soils (e.g. 0.2–3.0 mg l⁻¹, Piirainen *et al.* 2002). However, the DON concentrations in the centrifuged soil solution collected from the BC and C horizons were at a relatively similar level as compared with those measured from percolation water at a depth of 40 cm (Piirainen *et al.* 2002, Lindroos *et al.* 2016).

Compared with the NH₄-N and NO₃-N concentrations the DON concentrations in the O horizon were high. The DON concentrations

remained several times higher in both the E and B horizons than the respective $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations, indicating the more contributing role of the organic form of nitrogen over the inorganic forms in the centrifuged soil solution. However, the DON concentrations were at low and very similar levels as the $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations in the BC and C horizons. The concentrations of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ in the centrifuged soil solution were low in all the soil horizons and all the plots despite the amount of logging residues.

Our results support the well documented phenomenon that the higher the DOC concentrations are, the higher are also the concentrations of organic anions (A^-) (e.g. Kortelainen and Mannio 1990, Lindroos *et al.* 1995). The DOC concentration in the centrifuged soil solution was closely related to the degree of anion deficit, and therefore it seems possible that the anion deficit in centrifuged soil solution can be estimated solely based on the DOC concentration.

The estimated concentration of organic anions (A^-) had a strong relationship with the anion deficit. The estimated A^- concentration seemed to provide a good approximation of the organic anion concentration. The equation used takes into account pH and DOC concentration in the solution and estimates the dissociation level of organic acids (HA). As such, it gives a reasonable picture of the central role of dissociated organic anions in the ionic balance in the soil solution in our experiment likely because there was a clear difference in the DOC concentrations between some of the treatments (i.e. high DOC in the treatments 40 and 10 kg logging residues per m^2 compared to low DOC in the treatment 0 kg m^{-2}). The high DOC and A^- concentrations in the soil solution in the organic layer due to organic matter accumulation left on the forest floor influenced the ionic balance of the soil solution. The A^- was the dominant anion and with its increase in concentration in the organic layer, the concentration of base cations, particularly calcium, also increased. Calcium is probably released to the centrifuged soil solution through buffering processes from the cation exchange sites of the soil when the acidity (H^+) related to increased concentration of organic acids is buffered (Forsius *et al.* 1995). Organic

acids are also reported to increase the weathering rate of minerals leading to increased flux of base cations (Raulund-Rasmussen *et al.* 1998). Large accumulations of organic matter produce high concentrations of organic acids ($\text{HA} = \text{A}^- + \text{H}^+$; e.g. Forsius *et al.* 1995), and this undoubtedly has a potential to increase mineral weathering.

Based on the leaching of nutrients in percolation water below the large logging residue piles of similar size (40 kg m^{-2}) as in our study Lindroos *et al.* (2016) concluded that the most beneficial practice would be to leave logging residue in piles of small and moderate sizes that are as evenly distributed on the site as possible. Our results agree with this finding from the point of view of element concentrations in centrifuged soil solution, since also the highest element concentrations were associated with the large logging residue piles and an as even as possible distribution of logging residues would favor evenly distributed element concentrations. However, to assess what is the importance of soil solution extracted by centrifugation, further studies in bioavailability of nutrients for plants and microbes are still required.

We tried to select an as homogenous area as possible for the experiment in order to minimize the natural variation among the sample plots and subsequently to be able to find out the processes related to logging residue piles from other natural processes. However, it should be kept in mind that forest soil properties are known to vary considerably, and this fact may cause some difficulties to generalize our results. The effect of large organic matter accumulations on the soil solution chemistry was, on the other hand, very clear in our experiment.

In conclusion, the DOC and DON concentrations were higher in the organic layer in the centrifuged soil solution on the treatments with logging residues as compared with the no logging-residues treatment seven years after the treatments were applied. $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations were generally very low. It was possible to estimate accurately the anion deficit based on the DOC concentration in the soil solution, and increased concentration of DOC and organic anions strongly influenced the ionic balance of the centrifuged soil solution.

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